5-1999

The relationship of alignment hyperacuity to stereopsis

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Abstract

Human ability to monocularly detect spatial misalignment is functionally more precise than predicted by the diameter of one foveal cone. The spatial thresholds for vernier alignment are approximately 8 to 13 arc seconds of visual angle, which is more sensitive than expected. Although threshold stereopsis (another hyperacuity) seems to be approximately double alignment hyperacuity values, studies have not conclusively shown a definite relationship to ex1st. Additionally, these measurements have not been widely tested in clinical settings. This study examines the correlation between threshold stereoacuity and the monocular alignment hyperacuity measures. Twenty six subjects were evaluated measuring threshold stereopsis with the Mentor BVAT II Visual Acuity Tester and monocular alignment hyperacuity with software designed at Pacific University College of Optometry. This study supports a relationship of sum of one standard deviation of hyperacuity data distributed for each eye with stereopsis. However, the relationship is not statistically significant, most likely due to the lack of testing precision and variability in individual performance, specifically in binocular function and appreciation of stereopsis. Increased knowledge in the areas of monocular alignment hyperacuity and threshold stereopsis may aid optometric practitioners to better understand how these two factors play a role in such clinical conditions as unexplained asthenopia, amblyopia, strabismus and stereoacuity potential. However, clinical testing of an individual patient would not seem appropriate with this testing paradigm.

Degree Type

Thesis

Degree Name

Master of Science in Vision Science

Committee Chair

Scott Cooper

Keywords

alignment hyperacuity, binocular vision, separation discrimination, stereopsis, threshold stereoacuity

Subject Categories

Optometry

THE RELATIONSHIP OF ALIGNMENT HYPERACUITY TO STEREOPSIS

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A thesis submitted to the faculty of the
College of Optometry
Pacific Unviversity
Forest Grove, Oregon
for the degree of
Doctor of Optometry
May 1999

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Abstract

Human ability to monocularly detect spatial misalignment is functionally more precise than predicted by the diameter of one foveal cone. The spatial thresholds for vernier alignment are approximately 8 to 13 arc seconds of visual angle, which is more sensitive than expected. Although threshold stereopsis (another hyperacuity) seems to be approximately double alignment hyperacuity values, studies have not conclusively shown a definite relationship to exist. Additionally, these measurements have not been widely tested in clinical settings. This study examines the correlation between threshold stereoacuity and the monocular alignment hyperacuity measures.

Twenty six subjects were evaluated measuring threshold stereopsis with the Mentor BVAT II Visual Acuity Tester and monocular alignment hyperacuity with software designed at Pacific University College of Optometry. This study supports a relationship of sum of one standard deviation of hyperacuity data distributed for each eye with stereopsis. However, the relationship is not statistically significant, most likely due to the lack of testing precision and variability in individual performance, specifically in binocular function and appreciation of stereopsis.

Increased knowledge in the areas of monocular alignment hyperacuity and threshold stereopsis may aid optometric practitioners to better understand how these two factors play a role in such clinical conditions as unexplained asthenopia, amblyopia, strabismus and stereoacuity potential. However, clinical testing of an individual patient would not seem appropriate with this testing paradigm.

Key words: Alignment hyperacuity
Binocular Vision
Separation discrimination
Stereopsis
Threshold Stereoacuity

Introduction

Hyperacuity refers to perception at a level beyond that predicted by anatomical structures. Different types of hyperacuity exist, including misalignment, vernier, and oscillating movement displacement threshold hyperacuity. [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] Monocularly measured, vernier alignment hyperacuity is the ability to detect alignment of two points in space. The human visual system is very sensitive to changes in the position of objects in the visual field. Alignment hyperacuity thresholds are approximately 8 to 13 arc seconds of visual angle, smaller than the diameter of a foveal cone, and therefore considered a hyperacuity. [1, 11, 12, 13, 14] The current belief is that hyperacuity is the consequence of neural data processing by the visual system which is beyond the retinal level for foveal intercone spacing (25-30 arc seconds). [5, 17, 18] This neural processing that occurs is presumed to be located in the visual cortex.[17] Interestingly, people who are truly monocular may have hyperacuity as low as 3-8 arc seconds, and research has shown that performance will improve with practice in binocular individuals. [15, 16]

Hyperacuity studies have examined the effects changing target characteristics. Stimuli that are of opposite-contrast result in poorer hyperacuity threshold measurements than same-contrast stimuli.[19, 20] Hyperacuity can also differ under photopic and scotopic conditions. When comparing parafoveal vernier thresholds, cells of the magnocellular (MC) pathway gave larger responses than cells of the parvocellular (PC) pathway. This occurred at contrasts of 20% and below, but at higher contrasts the MC and PC pathway provided similar responses.[21]

Vernier hyperacuity performance has been tested in various age groups ranging from 20 to 85 years and found that vernier hyperacuity threshold was not found to vary with age.[22, 23] Hyperacuity is also unaffected by the minor optical changes that occur with age as determined by Odom et al.[6] However, retinal diseases that may occur as a result of the aging process can negatively affect vernier accuracy. Therefore alignment tasks are sensitive detectors of some retinal pathologies.

Alignment Hyperacuity and Threshold Stereopsis

There has been little solid baseline data from visual science research regarding normative data of hyperacuity and testing paradigms. Furthermore, the inter-relationships of various hyperacuities has had minimal attention. Alignment hyperacuity, tested monocularly, represents the range of x or y plane displacement that will be perceived as aligned by the patient. Stereoscopic tests require patients to detect a depth, or "z-axis." The monocular ability to detect a spatial shift should need to be summed to some degree for a binocular perception of a spatial shift. In other words, monocular cues should be able to vary within a "zone of insensitivity to positional change" without resulting in a binocular perception of change. Monocularly, these positional changes are perceived as lateral shifts, therefore oppositional monocular changes should binocularly combine to yield a "z-axis" perception of a change in depth. This sum of "monocular zones to insensitivity of spatial shifts" should indicate the perceptual threshold of a z-axis change, or threshold stereopsis.

This hypothesis has been explored since the early 1900's. Around 1900, Stratton was the first to find a rough equivalence of the monocular sensitivity to displacement threshold and stereoacuity threshold.[24] He suggested that the factor limiting stereoacuity may be the monocular sensitivity for spatial

displacement. This implies that stereoacuity thresholds are so similar in magnitude to hyperacuity thresholds that if stereoacuity were limited by monocular displacement sensitivity then the hyperacuity threshold should be one half the stereoacuity. Thus, the stereoacuity threshold would be equal to the sum of the hyperacuity of each eye. Although a recent study found no direct relationship between hyperacuity and stereopsis, minimal data was gathered in this study.[15]

The lack of valid baseline knowledge about hyperacuity and its relation to threshold stereoacuity may be withholding optometric practitioners from understanding and/or testing certain aspects of hyperacuity that might be of importance clinically. For instance, testing hyperacuity may be useful for predicting potential stereoacuity after strabismus therapy, monitoring improvement in amblyopia therapy to determine when increased binocular rivalry may create binocular difficulties, and determining a possible reason for unexplained asthenopia.

This study is designed to record hyperacuity for each eye and threshold stereoacuity in a normal adult population and determine if there is a correlation between hyperacuity and threshold stereoacuity. The study will use only easily accessible, affordable, and creatable software and hardware in order to allow testing to be easily applied in a clinical setting.

Methods

Protocol

Subjects:

The subjects for this experiment were twenty six students from the Pacific University College of Optometry. Subjects for the study were obtained on a volunteer basis. Criteria which qualified a subject to participate in the study were the following: a comprehensive vision and ocular health examination within the past year, visual acuity of at least 20/20 through habitual prescription (OD, OS, OU), no previous history of amblyopia or strabismus, no vertical heterophoria greater than 1/2 pd, no lateral heterophoria greater than 5 pd esophoria or 10 pd exophoria, and no ocular or systemic disease.

Pretesting:

Prior to testing, each subject was screened for the above criteria in a brief pretesting session. A brief patient history was followed by visual acuity measurement using a projected Snellen chart at 6m and a Snellen near acuity card at 40 cm. Next, a distance Maddox Rod test was performed to screen for vertical heterophoria. Finally, unilateral and alternating cover tests were performed with prism neutralization to screen for heterophoria and strabismus.

Threshold Stereopsis:

Threshold stereopsis was assessed with the Mentor BVAT II Visual Acuity Tester under normal room illumination. The BVAT was set for 15 arc seconds at a testing distance of 3 meters. Each subject was moved from a position where they could not detect the disparate target on the BVAT screen, to a position where they could detect the disparate target on the BVAT screen. The distance that the subject was able to identify the disparate target three out of five attempts was measured to the nearest centimeter. This measured distance was used to calculate threshold stereopsis for the subject via comparison to the calibrated distance for the BVAT (15 arc seconds and 3 meters). The formula used for calculation of threshold stereopsis is as follows:

$$T=(3.0/D)x15$$

Key:

3.0= calibrated testing distance for BVAT II (meters)

T= threshold stereoacuity calculated for subject (arc seconds)

D= distance form the monitor to the subject 9 (meters)

15= disparity of the stereoacuity target (arc seconds)

Hyperacuity

Alignment hyperacuity was tested using software developed at Pacific University College of Optometry. The stimuli were presented on a 15" Macintosh color high resolution RGB monitor that was aligned adjacent to the Mentor BVAT. The hyperacuity testing was done under the same testing conditions as threshold stereopsis testing. The subject was instructed to sit in a chair in front of the Macintosh monitor at the same distance threshold stereopsis was detected. Once seated, one of the subject's eyes was patched and a computer mouse was placed on the table in front of them. During the testing procedure, the screen displayed two dots five arc minutes in size, one above the other, separated by one arc minute. The bottom dot was held at a constant spot and the top dot was randomly displaced by the computer to the left and to the right of the bottom dot. With each trial, the subject was instructed to move the mouse in a horizontal fashion to line up the top dot directly above the lower. Each subject was encouraged to be as accurate as possible in determining alignment of the dots. When the subject believed the dots to be aligned, the subject clicked the mouse, the value of any lateral offset was registered within the software and the computer displaced the top dot once again. The subject aligned the dots a total of 150 times for each eye to allow an accurate assessment of their monocular vernier hyperacuity. Data collection was broken down into 6 sets of 25 trials with a 10-15 second break between sets. The subject was kept monocular during the entire testing procedure. The same procedure was followed for testing monocular alignment hyperacuity for the subject's other eye.

Fixation Disparity

Immediately following alignment hyperacuity, fixation disparity was measured using the Mentor BVAT II Acuity Tester. Fixation disparity was measured under the same testing conditions and at the same test distance as alignment hyperacuity was tested. The fixation disparity measurements were used for a simultaneous study analyzing the relationship between alignment hyperacuity and fixation disparity.

Data Handling

All data obtained was entered in tabular format into Excel 4.0 spreadsheet program. Alignment hyperacuity data was grouped and organized into a descending column of alignment points for each eye respectively. Outliers in these columns were determined on the basis that if the greater value of two sequential values was more than 50% greater than the lesser value, the greater value was not used in further calculations. This method typically resulted in 2 or 3 alignment points on each end of the scale treated as outliers and not used in further calculations.

The data analyzed provided a very narrow curve of distribution. Predicted threshold stereopsis values were calculated using the portion of each eye's curve that would result in a convergent stereopsis cue. The peak of data distribution was estimated based upon greatest frequency for a given hyperacuity measurement. This value was often extrapolated from the most common central 2 or 3 values of the subject's hyperacuity data. This extrapolated value was

considered the subject's own point of perfect alignment with all other hyperacuity data points lying on either side of this point. The hyperacuity data considered for the right eye consisted of all data points to the left of the peak of the data distribution. The hyperacuity data considered for the left eye consisted of all points to the right of the peak of the data distribution.

Results

To analyze the stereopsis and hyperacuity data for comparison, a two-tailed T-test for a within subjects design was run. The first T-test compared Real Stereopsis and the Calculated Stereopsis (One Standard Deviation from the peak value divided by two). The rationale for this comparison is that One Standard Deviation from the peak value may be the point where the offset would be noticed approximately 50% of the time given the typical point distribution. It is possible that the additive of the monocular offset of each eye could be perceived as a cue for stereopsis. The result of this T-test revealed a mean difference of -1.508 arc seconds ($P<.6162$). A scatter plot illustrates the relationship between the two variables listed above (see figure 1).

The second T-test compared Real Stereopsis and Calculated Stereopsis (One Standard Deviation from the peak value). The rationale for this comparison is that One Standard Deviation of offset in each eye may be necessary to perceive cues for stereopsis. Results of the T-test showed a mean difference of -31.474 arc seconds ($p<.0001$). A scatter plot compares the two variables listed above (see figure 2).

FIGURE 1:

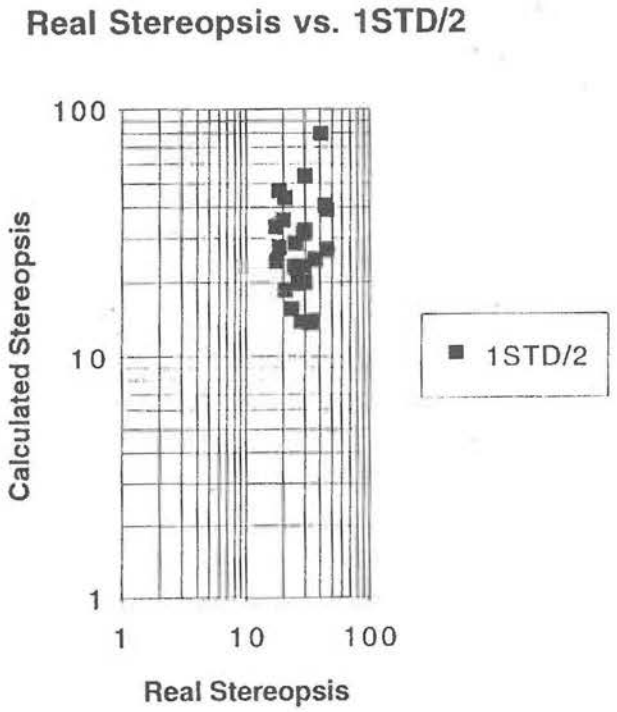
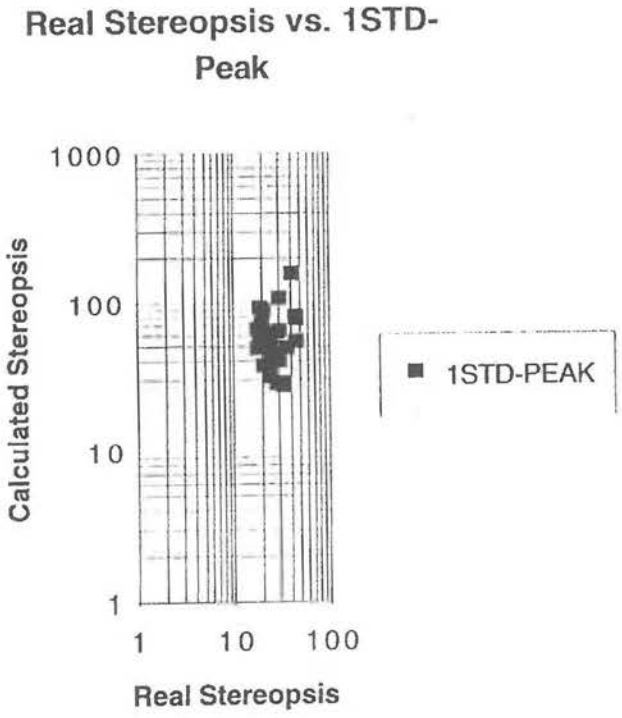


FIGURE 2:



Discussion

Recent findings indicate that there is a statistically insignificant correlation between threshold stereoacuity and the sum of monocular misalignment hyperacuities, although the results must be interpreted carefully. The trend towards significant correlation is obvious, but variables discussed later confirmed a relatively small subject pool. Our findings where similar to those found by Cooper et al.. They too found a significant correlation, however threshold stereoacuity was compared to the sum of the comparatively insensitive misalignment detection hyperacuity findings.[25] Our experimental design was essentially identical to their study however we were able to obtain more sensitive hyperacuity data. Results from the above mentioned studies were seemingly different from previously published research by McKee et al[8] which investigated the relationship between stereoacuity judgments to several other positional judgments, rather than the direct correlation test presented in our study. The McKee et al. study also used a different experimental design and the subject pool was much smaller. McKee et al. did not find a statistically significant correlation between hyperacuity and stereopsis.

Threshold stereopsis appears to be significantly different when compared to the sum of monocular misalignment hyperacuities. If test designs were found to support this relationship, the clinician could compare a patients performance on hyperacuity tasks to performance on stereoacuity tasks. If stereopsis is found to be comparatively deficient, it may be possible to measure OD and OS hyperacuities to predict potential stereopsis after therapy. An amblyopic eye which shows improvement with therapy should also show rapid improvement in hyperacuity in the poorer eye and in turn marked improvement in stereopsis. Comparison of these values may give valuable insight into the degree of perceptual improvement and potentially be an index of increased stress on

binocularity as monocular skills improve. However, current results indicate that this testing is not useful on an individual patient basis.

Many features of this study design may have contributed to the lack of statistical support for the hypothesis. The test design may have been relatively insensitive compared to the visual findings being explored. The test duration may have been too long, which may have increased subject error or variance in hyperacuity testing. Additionally, there may have been uncontrolled limitations to stereopsis perception such as instability of accommodation and/or vergence, poor stereopsis appreciation, or even patient attention.

A substantial amount of research has been done on hyperacuity and its relation to amblyopia and visual deprivation. Monocular visual deprivation in cats results in loss of vernier acuity which supports the relationship found in human amblyopes. Such studies further suggest that animal models could be useful for assessment of the abnormalities present in the amblyopic human visual system.[2] Additional studies have compared different types of amblyopia with hyperacuity and revealed that strabismic amblyopes show more loss to hyperacuity than anisometropic amblyopes. [13,17] Further studies should determine the degree hyperacuity can be improved with therapy and what factor it has in binocular perception and asthenopia.

It has been suggested that vernier acuity, a hyperacuity task, can be improved with training. Vernier acuity is said to be a perceptual learning effect specific for a visual field location.[26] For instance, an observer practicing vernier acuity for vertical lines cannot transfer learning to vernier acuity measured for horizontal lines.[12] One suggestion for specific learning is that performance improvement due to training might represent a kind of "fine tuning" in the mechanisms underlying visual tasks such as vernier acuity.[27] An alternate suggestion has been that there is a narrowing of orientation characteristics of

vernier acuity in the course of learning.[28] A large number of neurons are responsible for the orientation mechanism that signals vernier offset and of these neurons some may be broadly-tuned while others more narrowly-tuned for orientation. Reorganization produced by learning may represent selective weighting of the neurons that comprise the psychophysical mechanism, such that the narrowly-tuned neurons are given more weight.[28] Regardless of the mechanism, it does seem plausible to train certain aspects of hyperacuity. Further studies should then be focused on improving visual processing skills in amblyopic patients by training hyperacuity.

Administration of hyperacuity testing, in the form presented, takes about 25 minutes. It is simple enough to delegate testing to trained support staff. Testing hyperacuity may prove to be of great benefit depending on the type of patient, practice emphasis and results of further research.

In summary, our results show that a relatively normal binocular system should have a threshold stereoacuity approximately equal to the sum of one standard deviation of the distribution of monocular alignment hyperacuities. The statistically insignificant link should cause guarded use of these comparisons in a clinical population. Further study or modified test designs may improve the sensitivity and usefulness of such testing.

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APPENDIX

Patient	Hyperacuity OD	Hyperacuity OS	Stereopsis	Fixation Disparity
CJB	-3.59	-29.57	34.0"	0.45'EXO
JIK	-17.85	-13.81	29.0"	0.58'EXO
KCC	-0.30	-12.83	20.7"	0.14'EXO
RHW	7.35	-12.97	28.1"	0.19'ESO
SAS	4.10	-7.26	32.8"	0.22'ESO
SJS	18.41	0.47	25.7"	0.17'EXO
TLU	-10.45	-14.68	45.0"	0.60'ESO
VHB	4.93	-2.02	30.0"	0.80'EXO
WKL	-18.14	-18.60	24.7"	1.15'EXO
CLB	-15.55	-20.34	17.8"	0.48'ESO
DRC	-10.14	-0.19	20.0"	0.93'ESO
MF	2.36	-6.88	30.0"	3.00'ESO
JAR	-7.59	-10.94	36.7"	0.98'EXO
RDZ	11.96	-12.44	29.0"	0.97'ESO
CBL	-2.54	7.66	45.0"	9.90'ESO
SKC	8.36	-0.58	30.0"	0.40'ESO
BAO	-5.49	0.77	26.5"	0.88'EXO
CWP	-44.14	-30.45	18.75"	012'ESO
KJB	-33.05	-18.20	18.25"	1.62'EXO
JBA	-1.37	-9.44	23.68"	0.47'EXO
TLB	11.30	16.06	20.45"	2.32'ESO
LAS	-4.63	2.96	17.6"	0.82'ESO
KBR	-11.86	-27.17	25.0"	1.17'ESO
BCC	-25.69	-16.87	43.90"	0.29'EXO
MRJ	-5.84	-6.67	25.90"	1.90'ESO
MLF	4.07	-1.01	40.90"	2.45'ESO